



## MODELING THE IAQ IMPACT OF HHI INTERVENTIONS IN INNER-CITY HOUSING

SJ Emmerich\* and C Howard-Reed

Building and Fire Research Laboratory, National Institute of Standards and Technology, Gaithersburg, MD, USA

### ABSTRACT

The U.S. Department of Housing and Urban Development's Healthy Homes Initiative is addressing a wide range of indoor air quality (IAQ) concerns to improve urban housing conditions and protect the health of children. To evaluate the impact of potential interventions on indoor contaminant concentrations and occupant exposures, a simulation study was conducted using the multi-zone IAQ model CONTAM. The model was used to predict ventilation rates, contaminant concentrations of carbon dioxide, carbon monoxide, nitrogen dioxide, water vapor, particles, radon, and volatile organic compounds and occupant exposures for a baseline case and for eight different interventions, which included source control, filtration, local exhaust ventilation and dilution ventilation. While source control interventions were always the most effective on an individual contaminant basis, not all sources of indoor contaminants can be removed. On the other hand, interventions impacting air change rates, such as ventilation and envelope tightening, can either increase or decrease contaminant concentrations depending on the origin of the contaminants.

### INDEX TERMS

exposure, modeling, residential building, ventilation, contaminants.

### INTRODUCTION

Residential indoor air pollutants of concern include: combustion byproducts, volatile organic compounds, radon, and bioaerosols (Tobin et al., 1992; Sherman, 1999). Many of these contaminants are often measured at higher concentrations in lower income urban housing (Laquatra et al., 2002; Brugge et al., 2002). These residences are typically in the greatest need of remediation. As such, the U.S. Department of Housing and Urban Development (HUD) has made it a priority to identify wide-reaching intervention strategies that can be feasibly implemented to improve the indoor air quality (IAQ) in lower income homes. As part of this effort, the HHI program is funding several demonstration projects to implement interventions that correct many of the IAQ problems found in lower income urban homes. Due to the costs of fieldwork, however, the demonstration projects are only able to implement a limited number of interventions in a small number of homes. A more feasible way to prioritize the intervention strategies is through modeling. A modeling approach allows the evaluation of many potential interventions under a wider variety of conditions to help provide a knowledge base for recommending the most effective strategies. Such modeling can also be used to evaluate the interventions for possible unintended negative impacts. Thus, model results have the potential to provide tremendous insight toward the improvement of IAQ in urban housing with multiple deficiencies.

### SIMULATION METHOD

The simulation program used in this study is a multizone IAQ and ventilation model, CONTAM (Walton and Dols 2003). The multizone approach is implemented by constructing a building model as a network of elements describing the flow paths between the zones of a building. After calculating the airflow between zones and the outdoors, pollutant concentrations are calculated by applying mass balance equations to the zones. This paper describes the building model, sources, and interventions in general terms but due to space limitation does not include detailed values, which may be found in Emmerich et al. (2005).

### BASELINE BUILDING MODEL

A CONTAM model of an actual townhouse was used as a baseline building (Emmerich *et al.*, 2002), with modifications to make it more representative of lower-income urban housing. The townhouse is a three-story, three bedroom, three bathroom end-unit with a living space volume of about 250 m<sup>3</sup>. Since ventilation and IAQ

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\* Corresponding author email: [steven.emmerich@nist.gov](mailto:steven.emmerich@nist.gov)



performance vary by climate, the house was modeled in Boston, MA, Seattle, WA, and Miami, FL for one week of each season. A simple recirculating air handling system (AHS) in the model was “operated” based on weather. To account for occupant-generated contaminants and to account for occupant exposure to indoor contaminants, a family of five was assumed to occupy the townhouse. The occupants of the house included an adult male, adult female, and three children, with a schedule for each family member that specifies the time spent in each room of the house.

### Contaminant Sources and Sinks

The contaminants that were considered in the simulations include carbon dioxide (CO<sub>2</sub>), water vapor (H<sub>2</sub>O), carbon monoxide (CO), nitrogen dioxide (NO<sub>2</sub>), airborne particles, volatile organic compounds (VOCs) and radon (Rn). The sources of these contaminants were not intended to be comprehensive, but rather representative of some typical residential sources and to provide insight into each of the individual contaminants. Also, some of the sources produce additional contaminants beyond the ones considered (e.g., unvented combustion appliances produce CO<sub>2</sub>, H<sub>2</sub>O, and particles but were not included as a source of these contaminants in this study).

The only indoor source of CO<sub>2</sub> considered for this study was the respiration of the occupants. The CO<sub>2</sub> generation rates were based on ASHRAE Fundamentals Handbook (2001a).

Representative water vapor sources included respiration and perspiration of occupants, bathing, cooking, and dishwashing. The occupant water vapor generation rates were based on ASTM (1994). The water vapor generation rates and schedules for bathing, cooking and dishwashing were based on an earlier NIST study (Persily, 1998).

The indoor sources of CO and NO<sub>2</sub> included a gas stove and an unvented space heater. The generation rates for the gas stove were based on Persily 1998. The unvented space heater was only operated during the winter seasons in Boston and Seattle and used generation rates from Emmerich and Persily 1996.

The model included 5 particle size ranges (0.3 µm to 0.5 µm, 0.5 µm to 1.0 µm, 1.0 µm to 2.5 µm, 2.5 µm to 5.0 µm, 5.0 µm to 10 µm), which correspond to size ranges commonly measured in the field (Wallace and Howard-Reed, 2002; Howard-Reed et al., 2003). Indoor particle sources included cooking (for generation of smaller particles) and changing of kitty litter twice a week (for generation of larger particles).

The study includes two nonspecific VOCs as surrogates for two types of sources. VOC1 was generated in each room of the house at a rate proportional to the floor area based on an average of published flooring emission rates for toluene (U.S. EPA 1999). VOC2 was generated by a burst source based on an emission rate for floor cleaning (Wallace 1987).

A pressure-dependent radon source described in an earlier NIST report (Fang and Persily, 1995) was included in the basement zone of the model with a generation rate that yielded reasonable concentrations.

Outdoor water vapor concentrations were based on the humidity ratios in the weather data. Outdoor concentrations of CO, NO<sub>2</sub>, CO<sub>2</sub>, and VOCs were based on those used in earlier studies (Persily 1998 and Emmerich and Persily 1995). Outdoor particle concentrations were based on measurements outside a research townhouse (Wallace and Howard-Reed 2002).

The loss of contaminants due to adsorption, deposition and decay were also included in the models. Reversible sink effects for H<sub>2</sub>O and VOCs were modeled with sink elements based on the boundary layer diffusion controlled (BLDC) model available in CONTAM. Particles were also removed in the baseline cases by a typical furnace filter in the AHS.

### Scenarios/Interventions

The housing repairs/interventions included some being performed by HUD’s NOFA grant awardees and requirements in ASHRAE 62.2-2004:

*Removal of unvented space heater:* For winter baseline simulations in Boston and Seattle, an unvented space



heater was used in the living room and constituted a source of NO<sub>2</sub> and CO. For the intervention, the space heater emissions were not included in the winter simulations.

*Upgrading gas stove:* For the baseline case, relatively high emission rates of NO<sub>2</sub> and CO were assumed based on values in a previous report (Emmerich and Persily 1995). Lower stove emission rates associated with a more efficiently operating stove (CO rate reduced by 97 % and NO<sub>2</sub> rate was reduced by 85 %) were compared with the baseline values.

*Operation of gas oven to heat home:* In addition to using gas ovens for cooking, some residents use them as a heat source in the winter (Brugge *et al.* 2002). To assess the impact of ceasing this practice, separate simulations were performed using a stove to heat the house for 4 hours every evening in the winter.

*Enhanced particle air cleaner:* The baseline filter was replaced with an air cleaner with higher removal efficiencies of: 36 % for 0.3 µm to 0.5 µm, 49 % for 0.5 µm to 1.0 µm, 62 % for 1.0 µm to 2.5 µm, 62 % for 2.5 µm to 5.0 µm, and 62 % for 5.0 µm to 10 µm. (Emmerich and Nabinger 2001).

*Installation of air-conditioner:* For the Boston and Seattle summer simulations, an air-conditioner was added to the model, which operated the first 10 minutes of every hour and removed moisture at a rate of 17 % (based on Persily 1998) and particles at a rate equivalent to the typical furnace filter.

*Kitchen and bathroom exhaust fans:* This intervention involved the inclusion of intermittent kitchen and bathroom exhaust fans that meet the requirements of ASHRAE Standard 62.2 (2004). The kitchen fan has airflow of 47 L/s and was operated during cooking events. The bathroom exhaust fans each had airflow of 24 L/s and were operated during showers.

*Tightening the envelope:* A common suggestion to reduce residential energy consumption is to tighten a house's exterior envelope. To model this intervention, all exterior envelope leakage area elements were reduced by 40 % from the baseline case.

*Mechanical whole-house ventilation:* ASHRAE Standard 62.2 requires use of a mechanical ventilation system to provide outdoor air to a dwelling (ASHRAE 2004). The amount of outdoor air is based on the house's floor area and number of bedrooms. For all seasons in Boston and Seattle, a 24 L/s exhaust fan was continuously operated in the master bathroom. Due to Miami's hot and humid climate, a mechanical supply system was used instead of an exhaust system. Since the outdoor air was provided on the same schedule as the air-conditioner operation the outdoor air was supplied at a rate of 142 L/s to provide the equivalent of 24 L/s continuous ventilation.

## RESULTS

This section briefly summarizes the results of the simulations for each intervention/scenario simulated. Emmerich *et al.* (2005) report detailed air change rate and concentration results.

*Upgrading gas stove:* Upgrading the gas stove results in lower NO<sub>2</sub> and CO concentrations year round. In fact, it was the single most effective intervention at reducing these contaminants in all climates. In general, older combustion appliances have lower efficiencies and tend to emit more pollutants. Although a gas stove was used to illustrate this point in this project, the intervention would be effective for reducing contaminants for any combustion appliance (*e.g.*, furnace, gas dryer, *etc.*).

*Operation of gas oven to heat home:* Educating occupants of the potential dangers of using a gas oven for heat is the least expensive intervention strategy examined. Operating a gas oven to heat a house is a dangerous practice that can elevate concentrations of CO and NO<sub>2</sub> to unhealthy, even fatal, levels (see warning at <http://www.epa.gov/iaq/pubs/combust.html>). For this project, using the gas oven to heat the house resulted in the second highest average winter concentration of CO, assuming a properly operating oven was used. If a faulty oven had been used, the occupants' exposure to CO would have been much higher and may have exceeded fatal levels. Unfortunately, this practice does persist in lower income housing when the residents do not understand the risks involved. Stopping this practice is a source control option that would prevent excessive exposure to CO and NO<sub>2</sub> at little to no cost to the resident (unless faulty heating equipment needs to be replaced, which would entail significant cost).



*Removal of unvented space heater:* Using only properly vented space heaters would have a similar impact on indoor air concentrations of CO and NO<sub>2</sub> that were realized for ceasing the use of a gas oven for heat. Venting the combustion products from space heaters to the outside would essentially remove these pollutants from the living space, thereby significantly reducing occupants' exposure to CO and NO<sub>2</sub> in cold climates. This intervention would require both education for the occupants and the installation of an exhaust vent, if needed.

*Enhanced particle air cleaner:* Air cleaning reduces contaminants originating both indoors and outdoors with no negative impact on other contaminant concentrations. Most homeowners, however, only have access to air cleaners that remove particles, limiting the scope of the intervention. While an effective intervention for removing particles, an air filter only works when the HAC system is operating. For this project, the HAC system was operated for cold seasons in Boston and Seattle and hot seasons in Miami. In the other seasons, the HAC system was off and the air filter was not removing any particles. As a result, this intervention was only useful in cold or hot climates. This intervention would also be effective in more temperate seasons, however, it is important to consider the balance between first and operating costs and benefit from reducing particle concentrations.

*Installation of air-conditioner:* Despite a relatively short operation time assumed in the modeling effort, the air-conditioner significantly decreased average humidity levels in the house. In fact, the benefit of operating an air-conditioner for one season in Boston and Seattle outweighed the benefits of other interventions operated year-round. Again, there is a need to consider both first and operation costs along with the benefits obtained by limiting relative humidity to levels low enough to prevent mold, allergens, and other indoor air problems.

*Kitchen and bathroom exhaust fans:* The exhaust fan was the most effective intervention strategy to reduce peak concentrations associated with cooking and showering. This reduction in concentration during source events had a significant impact on the occupants' exposure to CO, NO<sub>2</sub>, PM<sub>2.5</sub>, PM<sub>10</sub> and H<sub>2</sub>O. It was the single most effective intervention for exposure to PM<sub>2.5</sub> and PM<sub>10</sub> in most climates. The increased air change rate due to exhaust fan operation also reduced the concentrations of contaminants from sources in other parts of the house (e.g., VOC1 and radon). The downside of this intervention was the increase in concentrations of contaminants originating outdoors. This negative impact was significant for PM<sub>10</sub>, PM<sub>2.5</sub>, and H<sub>2</sub>O in Miami. The benefits of using an exhaust fan during source events, however, far outweighed the negative impacts. In fact, project results showed that using the exhaust fan during more source events (e.g., cleaning in kitchen or bathroom, or dishwasher operation) would have reduced concentrations and exposures even more. If there is no exhaust fan installed or if the current fan does not vent to the outside, there will be an installation cost in addition to an operating cost associated with this intervention. However, in some cases, it is a matter of educating the occupants to turn on the fan during source events.

*Mechanical whole-house ventilation:* Continuous mechanical ventilation is another intervention that affects all indoor air contaminants, but not always positively. Mechanical ventilation was most effective at reducing contaminants primarily originating indoors via a continuous source (e.g., CO<sub>2</sub>, Rn, and VOC1). Mechanical ventilation also diluted concentrations from indoor burst sources (e.g., CO, NO<sub>2</sub>, and VOC2). Contaminants originating primarily outdoors were negatively impacted (e.g., H<sub>2</sub>O in Miami and particles). The negative impacts of mechanical ventilation tended to be greater than those of the exhaust fan intervention, since the outdoor air was continuously added with mechanical ventilation and only added during source events with the exhaust fan. Effective filtration could mitigate this impact. Adding mechanical ventilation using an exhaust fan is the least expensive option, whereas adding outdoor air supply is likely to be more expensive. There is also an incremental cost associated with cooling or heating the added outdoor air.

*Tightening the envelope:* Tightening the building envelope has long been recommended for improving energy efficiency, but the resulting reduction in air change rate has dramatic effects on pollutants originating indoors. In fact, it was the single worst intervention in terms of increasing the concentrations of CO, CO<sub>2</sub>, NO<sub>2</sub>, PM<sub>2.5</sub>, Rn, VOC1, and VOC2. Although it was most effective at reducing H<sub>2</sub>O in Miami, PM<sub>10</sub>, and PM<sub>2.5</sub>, tightening should not be implemented without considering the need for supplementary outdoor air.

## SUMMARY AND DISCUSSION

Of all the intervention strategies analyzed for this project, the operation of an exhaust fan during source events had the broadest positive effect. This benefit would have been greater if it were operated during more of the source events. If only two interventions can be implemented, then the exhaust fan and more efficient air filter should be used, with the assumption that the HAC system is operating at least 15 % of the time. However, considering the possible large impact on a single contaminant that is possible through source control, any intervention effort

should include a review of sources, particularly large or unusual ones. These recommendations are based on results for a specific house and do not account for cost or contaminant toxicity. Future recommended research includes broadening the scope of the building type, incorporating an economic analysis of the options, and perhaps assigning a ranking of contaminants based on human health effects.

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